

A MULTIPLEXED FM DATA SYSTEM WITH IDENTICAL CHANNEL CHARACTERISTICS

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Summary: Seven systems each with ten FM constant bandwidth channels are discussed. The required bandwidth for the seven systems and the respective maximum deviation are 800 kc, 400 kc, 200 kc, 100 kc, 50 kc, 25 kc, and 12.5 kc; ± 16 kc, ± 8 kc, ± 4 kc, ± 2 kc, ± 1 kc, ± 0.5 kc, and ± 0.125 kc. The adjacent channel interference problem is examined as are the problems associated with maintaining time correlation between the channels of any one system. The results of tests on a record/reproduce sequence for a typical system are given.

Introduction

The characteristics of the standard IRIG FM subcarrier system are well known to the industry. In brief, the system consists of 18 FM subcarriers which can be deviated $\pm 7.5\%$ and the channels are separated by guard bands which vary from 0.62 to 0.95 of bandwidth. This system has been very successful and some measure of that success can be traced to the inherent good features of a constant percentage deviation system. From the data handler's point of view, the system provides a set of channels which range from 6 cps to 2100 cps. The constant percentage system also has its advantages from the equipment manufacturer's point of view. Since the bandwidth bears the same relation to the center frequency regardless of the value of the center frequency, all designs for oscillators and frequency determining networks can be normalized. This greatly aids standardization of designs and confines the development problem. In short, this feature permits a manufacturer to come out with a new line of subcarrier oscillators or discriminators without a channel by channel development.

It is doubted that the FM subcarrier telemetry art could be where it is today had it not been for the ease of manufacturing standardization that is inherent in the constant percentage deviation system. On the other hand, the limitations of the constant percentage system are also straightforward. The foremost limitations arise because every channel has a different bandwidth and a different delay of intelligence. This is very restricting for in today's work, there are many problems where it is necessary to telemeter the outputs of many identical transducers and also it is required to have time correlation between the data channels. Such data requirements call for systems comprised of channels of constant bandwidth per channel rather than constant percentage deviation per channel. In constant bandwidth

systems, the percentage deviation varies from a large percentage deviation at the lower frequency channels to a progressively smaller percentage deviation as the channels go higher in frequency. The range of permissible percentage deviation is limited by the characteristics of the subcarrier oscillators and subcarrier discriminators. As the channel bandwidth becomes a progressively smaller percentage deviation of the subcarrier frequency, the drift and noise of the oscillators and discriminators become a progressively larger percentage of the channel bandwidth. As the deviation becomes a larger percentage of the subcarrier, it becomes progressively more difficult to maintain modulator and demodulator linearity and more difficult to filter the data from the subcarrier at the output of the discriminator. The limits on percentage deviation are, of course, arbitrary, but at present, DCS runs over the range from $\pm 4.5\%$ to $\pm 40\%$. These limits, of course, can be exceeded but at a further compromise with either drift, nonlinearity or subcarrier in the output.

When a broad analogue data bandwidth is available such as with the modern tape machines which run beyond one megacycle and one has a requirement for many channels of identical bandwidth and time correlation, then it is obvious that neither the constant percentage deviation system nor the constant deviation (bandwidth) system will suffice. The constant percentage system is not appropriate because every channel has a different bandwidth and the constant bandwidth system soon runs into the modulator and/or demodulator limitations.

To illustrate this problem, consider a requirement for as many identical data channels as possible, each with 1 kc data bandwidth, all channels time-correlated and all to be telemetered in 250 kc bandwidth. Let the requirement for channel interference noise be such as to necessitate a modulation index of 2.0 for each channel. This requires a maximum carrier deviation of ± 2 kc. Recalling that the range of percentage deviation permitted by the modulators or demodulators runs from 4.5% to 40%, then the minimum percentage deviation of 4.5% will give the highest permissible channel at 45 kc ± 2.0 kc while the largest permitted percentage deviation will set the lowest channel at 5.0 kc ± 2.0 kc. From this it is seen that the spectrum between the 45 kc channel and the upper limit of 250 kc is precluded by the minimum permitted deviation.

To overcome this basic problem, the technique of Frequency Translation^{1, 2} has been used successfully. In this technique, groups of constant bandwidth channels have been heterodyned against a reference carrier so as to relocate the channels as the sidebands about the carrier. For instance, in the example under consideration, the channels are in the range from 5.0 kc to 45 kc. This spectrum can be shifted with acceptable degradation by heterodyning the group against, say, a 100 kc reference carrier. The output from such a heterodyne process would have the 5.0 to 45 kc spectrum translated to the bands of 100 kc $\pm$ (5.0 to 45 kc). Since all the required channel signals are contained in either sideband, only one need be recorded or transmitted. After translation, the data is located in the spectrum as a very small percentage deviation, but prior to demodulation by a subcarrier discriminator, it is detranslated to its original location in the spectrum. By this technique of translating up in frequency then detranslating down, the limitations of the subcarrier

oscillators and discriminators have been circumvented.

Ten Channels of Constant Bandwidth-Time Correlated Systems:

The ease of design standardization inherent when the bandwidth of each channel of a system is a certain percentage of the carrier has been emphasized. It has also been pointed out that in a given system of constant bandwidth, the normalization feature is not present. However, closer examination of the general problem shows that all of this normalization feature need not be lost.

Figure 1 is a chart of standard DCS constant bandwidth data systems. Each system is alike in that it contains ten constant bandwidth channels plus a reference channel. However, each system has a different maximum deviation starting from ± 250 cps and increasing by octaves up to ± 16 kc. The systems are composed of two sets of five channels which DCS has arbitrarily designated A thru E (not to be confused with IRIG lettered channels). It should be noted that the percentage deviation ranges from $\pm 4.7\%$ to $\pm 16\%$. This difference in percentage deviation causes an extra development burden. However, it should be noted that to go from one system to another is merely a scale change. This degree of standardization is very important for if special problems arise which require some range of frequencies not given by Figure 1, it is not a major design change to scale the entire set of A thru E channels. A system requiring a scale change is a minor effort while a system made up of channels with percentage deviations other than those of A thru E requires engineering design and evaluation. This is normally inefficient for both the manufacturer and the user.

To describe the make-up of the ten channel system, consider the 2 kc deviation-100 kc bandwidth system. It is seen that the lowest channel of the untranslated set is at 12.5 kc and the next four are spaced 7.5 kc between the band centers. Since the maximum deviation is ± 2 kc, the guard band is 3.5 kc which, in turn, is $7/8$ of the bandwidth. Note in translating that the highest translated channel is obtained by subtracting the 12.5 kc from 100 kc. If the lowest channel had been chosen lower than 12.5 kc, then the highest channel would be correspondingly closer to the 100 kc. This is a significant point and will be discussed further when the problem of recovering the reference is considered. The highest subcarrier channel of the untranslated set is 42.5 kc ± 2 kc. This is a $\pm 4.7\%$ deviation channel which approaches the minimum permitted percentage deviation value.

Next, consider the translated set. As indicated in Figure 5, the five subcarrier oscillators are summed to form a multiplex; then the composite signal is translated to the lower sideband of a reference carrier. To locate any of the translated A thru E bands, subtract the original center frequency from the reference carrier value. Note that the spacing between the lowest of the translated channels and the highest of the untranslated channels is twice the spacing between the other channels.

To recover the data after transmission or storage on tape, the upper set must be returned to its original location in the spectrum prior to

demodulation. This is true for two reasons: As mentioned, the drift and noise from a discriminator is correspondingly higher as the band becomes a smaller percentage of the center frequency but when using a tape machine, the consideration of wow and flutter is even more important. Wow and flutter on a machine is equivalent to a tape speed change which has the effect of changing all recorded frequencies by the percent change in speed. When the band is a small percent of the carrier, then the percentage wow and flutter can become a very large percentage of the total channel bandwidth.

To illustrate, take the 100 kc bandwidth system and consider the two 12.5 kc ± 2 kc channels -- one untranslated, one translated. Let both these channels be recorded on a machine with a $\pm 1\%$ wow and flutter variation. The center frequency at 12.5 kc will vary ± 0.125 kc which is $\pm 3.1\%$ of the 4 kc bandwidth. However, the channel translated from 12.5 kc to 87.5 kc will vary .875 kc or $\pm 22\%$ of bandwidth. If one is looking for a $\pm 1\%$ system, then it is obvious that careful consideration must be given to the compensation of the wow and flutter. If the translated channel is detranslated against a fixed reference, the wow and flutter in the channel remains at the unacceptable $\pm 22\%$. If, however, the channel is detranslated against a reference obtained from the tape, then the wow and flutter problem is reduced to reasonable proportions. This is very evident from series of simple relationships.

$$\begin{aligned}\text{Untranslated Channel} &= 12.5 \text{ kc} \\ \text{Translated Channel} &= (100 - 12.5) = 87.5 \text{ kc} \\ \text{Reference} &= 100 \text{ kc}\end{aligned}$$

Let $\pm a\%$ wow and flutter speed variation be introduced.

$$\begin{aligned}\text{Untranslated Channel} &= 12.5 (1 \pm a) \\ \text{Translated Channel} &= (100 - 12.5) (1 \pm a) \\ \text{Reference} &= (100) (1 \pm a)\end{aligned}$$

Let the translated channel be detranslated against the reference with wow and flutter.

$$\begin{aligned}\text{Detranslated Channel} &= (100 - 12.5) (1 \pm a) - 100 (1 \pm a) \\ &= 12.5 (1 \pm a)\end{aligned}$$

Since this is identical with the expression for the wow and flutter on the 12.5 kc channel recorded untranslated, it is possible to use conventional wow and flutter compensation from a reference discriminator to further reduce the effect.

The Characteristics of the Ten Channel System:

The main concern of multiplexing FM subcarriers in a linear system is adjacent channel interference. To assure oneself that a new FM subcarrier system has adequate guard bands, one can do three things: compare the guard band structure to those of a known system, say the IRIG; compute the interference assuming sine waves modulating the adjacent channel and knowing the filter structure; and, finally, one can set up a channel and measure the interfering noise at various regions across the band. Comparing the ten channel systems' guard

band structure with IRIG, one finds that the ten channel system has a guard band which is 0.875 the channel bandwidth, while the lower IRIG guard band ranges from 0.6 to 1.0 times the channel bandwidth.

Figures 2, 3, and 4 give the various aspects of measuring adjacent channel interference. Figure 2 shows the RMS noise in a modulation index = 1.0 linear phase channel when the adjacent channels were deviated band edge to band edge by various sine waves whose frequencies ranged from a modulation index of 1.0 to a modulation index of 4.0. It can be seen that this worst case noise is less than 2% of a full band edge to band edge signal. Figure 3 shows how much the noise can be reduced by changing from a linear phase to a constant amplitude low pass. Figure 4 gives similar data for a modulation index = 2.0 system. This system is the maximum recommended only for the problems when the higher noise can be tolerated. Such a problem occurs in vibration data studies which require large bandwidth and accurate time correlation between channels.

Figure 5 is a ten channel record/playback configuration which applies to any of the systems shown in Figure 1. The top half of the figure diagrams the record portion while the bottom half gives the playback portion. Examining the record portion, the two like sets of five VCO's form two separate multiplexes -- one designated sub L, the other sub H. The sub L group is recorded in the lower sector of the recorder bandwidth and the sub H group is translated to the high end. The reference carrier is provided by a crystal controlled oscillator which can be part of the system or can be supplied to the system from the reference of a time code generator. The translator block in addition to containing the heterodyning modulator contains the necessary summing amplifiers, plug-in filter and line driver amplifier. On playback, the ten channels can be played back simultaneously using ten discriminators or it can be played back, a set of five channels at a time. The latter method affords a great saving in that only five discriminators are required.

The playback system is essentially the inverse of the record. The higher set is detranslated to its original location in the spectrum from which it is a conventional subcarrier demodulation problem. Figure 6 is given for a closer examination of the playback system. The two units of consideration are the reference discriminator and the detranslator. The reference is filtered by the band pass of the reference tuning unit. Since there is a time delay associated with filtering, the wow and flutter components are accordingly delayed. This delay is equalized by a plug-in delay line inserted between the tape output and the detranslator. The output of the unit to the discriminator's input bus can be switched from the front panel of the detranslator.

Figures 2 through 5 aid in evaluating the adjacent channel interference as function modulation index of the system. These curves describe the geometrical design of the system; i.e., the channel to channel spacing and guard band to data band ratio. In other words, the curves are really quite independent of the experimental apparatus and are solely a frequency spacing evaluation.

Figure 7 is a different breed altogether. It is a complete system test wherein the resultant data embodies many effects any of which could be improved or worsened by the characteristics of the various black boxes in the system.

Among the parameters of consideration are: harmonic output of VCO's; generation of intermodulation terms in the translating modulators; mismatch of time delay of the two-path detranslation system; poor wow and flutter compensation; the noise of the tape recorder; intermodulation caused by direct record and direct reproduce amplifiers; and numerous problems controlled by filter design.

The combination of Figures 2 and 7 give a measure of what can be expected of a ten channel system using today's equipment. It remains, however, a system problem and almost beyond the art of specifying each component black box. To emphasize this point, consider the problem of assigning a signal level to each channel plus the reference. If too high a signal is assigned to each channel, the total peak signal will exceed the linear range of the recorder and cause intermodulation noise. If the signal is too low, the recorder will give a non-optimum signal-to-noise ratio from the record/playback sequence. Figure 7 then is given as a guide of the type of performance that can be expected from a ten channel with reference recorded on a standard quality data tape machine.

The combination of this series of data systems and tape recorders is a natural marriage because just as the tape machine changes speed by factors of 2, so does the available tuning units required for data reduction. Consider the problem of recording fast transient data which is beyond the speed of practical galvanometer oscillographs. With the Figure 1 array of channels, these signals could modulate wide band, high frequency subcarrier oscillators -- be recorded at high tape speed -- be played back at reduced speed -- then demodulated by subcarrier discriminators whose output frequency range would match the frequency range of the oscillograph equipment. For real time applications, the wide band demodulation equipment is also available.

Figure 8 is given to show the physical size of the ten channel system, record and playback. Each occupies 3-1/2" panel height of a standard 19" relay rack. A typical configuration of the system sub units are spelled out at the bottom of Figure 6.

Time Correlation Between Channels:

Systems composed of channels of identical bandwidth are inherently systems with time-correlated channels. At first glance, this is not an obvious statement of fact but a short reflection on the definition of time delay and the characteristics of linear phase filters will bear it out. Assuming linear phase filters throughout the system and assuming the same total number of filters in each channel, and since there is a specific phase shift at filter cut-off, then it follows that the phase shift per unit bandwidth will be the same for all channels. The situation where each linear phase channel has the same total phase shift at the same cut-off is a restatement of equal envelope time delay defined as the slope of the phase versus frequency curve. The problem of time correlation then is one of specifying tolerances for the various filters in the system. The tolerance on the inter-channel

correlation will be the sum of the accumulated tolerances from the filters in each channel. We have found from design and production experience that when 1% components are used, the attenuation at the nominal cut-off of three-pole and five-pole passive filters can be mass produced and tested to a $\pm 1/4$ db tolerance. This is reflected as a $\pm 5\%$ variation in true cut-off, which means a $\pm 5\%$ tolerance of the phase shift at the nominal cut-off. The main sources of time delay variation are in the VCO output band pass filter and the discriminator output low pass. The other system filters are either broad band which have a short delay or are active filters with a tight tolerance such as the discriminator input bandpass filters.

From this information, one could set mass production tolerances on the phase shift at channel cut-off: The phase shift at channel cut-off for a modulation index of 1.0 is $\pm 12\%$; $\pm 7\%$ for a modulation index of 2.0 system and $\pm 5\%$ for a modulation index of 4.0 system. In different words, for a system made up of channels with a data cut-off of 1 kc, the approximate tolerance on the time correlation between channels would be:

± 25 usecs for a Modulation Index = 4 system
 ± 35 usecs for a Modulation Index = 2.0 system
 ± 60 usecs for a Modulation Index = 1.0 system

A typical calculation is based on a phase shift of 140° at cut-off for a five-pole linear phase low pass filter. This represents a delay of $\frac{140}{360} \times \frac{1}{f_c}$ or approximately one-half period of the cut-off frequency.

Then with a cut-off of 1 kc, the period is 1000 u sec. Then $1/2 \times 5\%$ of 1000 usecs = 25 u sec.

A similar time-correlation tolerance table could be constructed for any other data bandwidth. These tolerances are obtainable in production; if tighter tolerances are required, further effort could be made to equalize the channels. The engineering, evaluation, and production test effort figuratively goes up exponentially as the tolerances are tightened.

The foregoing discussion concerned itself with the general problem of time delay. There is a specific problem that was mentioned early in the paper that needs close examination. That is the problem of filtering the reference from the played back multiplex. When a carrier is run through a band pass filter, the envelope is delayed. The delay is inversely proportional to the bandwidth. In a five-pole linear phase band pass filter, the phase slope is approximately $300^\circ/\text{bandwidth}$. If the adjacent channel is close to the reference, the bandwidth of the reference filter must be made accordingly narrower. As the bandwidth is made narrower, the phase slope is progressively steeper and the time delay progressively longer. To equalize the delay in the data path with the delay in the reference path, it is necessary to insert a delay line. As the delay is increased, tolerance problems are encountered for the uncertainty in delay is given as a percentage of the total. Then, as the total rises, the uncertainty in the absolute rises proportionally. For this very practical reason, the lowest frequency channel of the set to be translated never is permitted to be as low as the maximum percentage deviation would have it. To illuminate -- with a 2 kc deviation system, the restriction of no greater than $\pm 40\%$ deviation would permit a channel at 5 kc $\pm 40\%$. This would put the translated channel at (100 -5) kc which would require

a narrow 100 kc reference filter which would, in turn, require a very large value of equalizing time delay.

References:

1. R. A. Runyan, "Frequency Translation of FM Subcarriers as a Means of Multiplexing Many High Frequency Data Channels"
2. O. J. Ott and W. P. McGarry, "Frequency Translation of FM Subcarriers," National Tele-metering Conference, May 1960

CENTER FREQUENCIES OF FM SUBCARRIERS OF 10 CHANNEL CONSTANT BANDWIDTH SYSTEMS

FIG. 1

Bandwidth & Reference	Max. Deviation	Five Untranslated Channels					Five Translated Channels				
		A	B	C	D	E	E'	D'	C'	B'	A'
12.5	0.250	1.56	2.5	3.44	4.87	5.3	7.18	8.12	9.06	10	10.9
25	.500	3.12	5	6.87	8.75	10.6	14.37	16.2	18.12	20	21.8
50	1.0	6.25	10	13.7	17.5	21.2	28.7	32.5	36.2	40	43.7
100	2.0	12.5	20	27.5	35	42.5	57.5	65	72.5	80	87.5
200	4.0	25	40	55	70	85	115	130	145	160	175
400	8.0	50	80	110	140	170	230	260	290	320	350
800	16.0	100	160	220	280	340	460	520	580	640	700

All Numbers in Kilocycles/sec.

System to Frequency
Scale



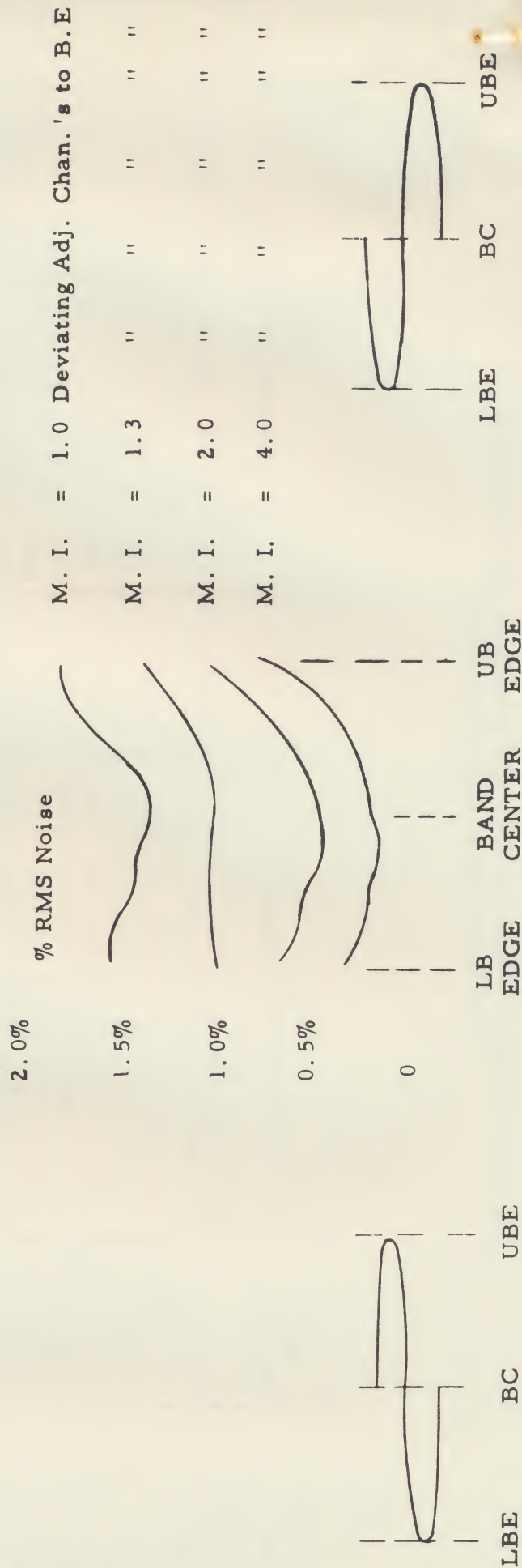
Percentage
Deviation 16% 10 7.3 5.7 4.7%

FIG. 2

MOD. INDEX = 1.0 System

Output Low-Pass Filter: 5 Pole Lin. Phase

RMS Noise
as % of Bandwidth Signal



MEASUREMENT OF ADJACENT CHANNEL INTERFERENCE BETWEEN CONSTANT BANDWIDTH CHANNELS.

FIG. 3

MOD. INDEX = 1.0 System

Output Low-Pass: 5 Pole Cons. Amp.

Guard Bands = 7/8 Data Band

RMS Noise As A %
of Bandwidth Signal

2.0

1.5

1.0

0.5

0

MOD. I. = 1.0 Signal Deviating
Adjacent Bands

MOD. I. = 1.3 Signal Deviating Adj. Bands

MOD. I. = 2.0 " " " "

MOD. I. = 4.0 " " " "

LBE BC UBE

LBE BC UBE

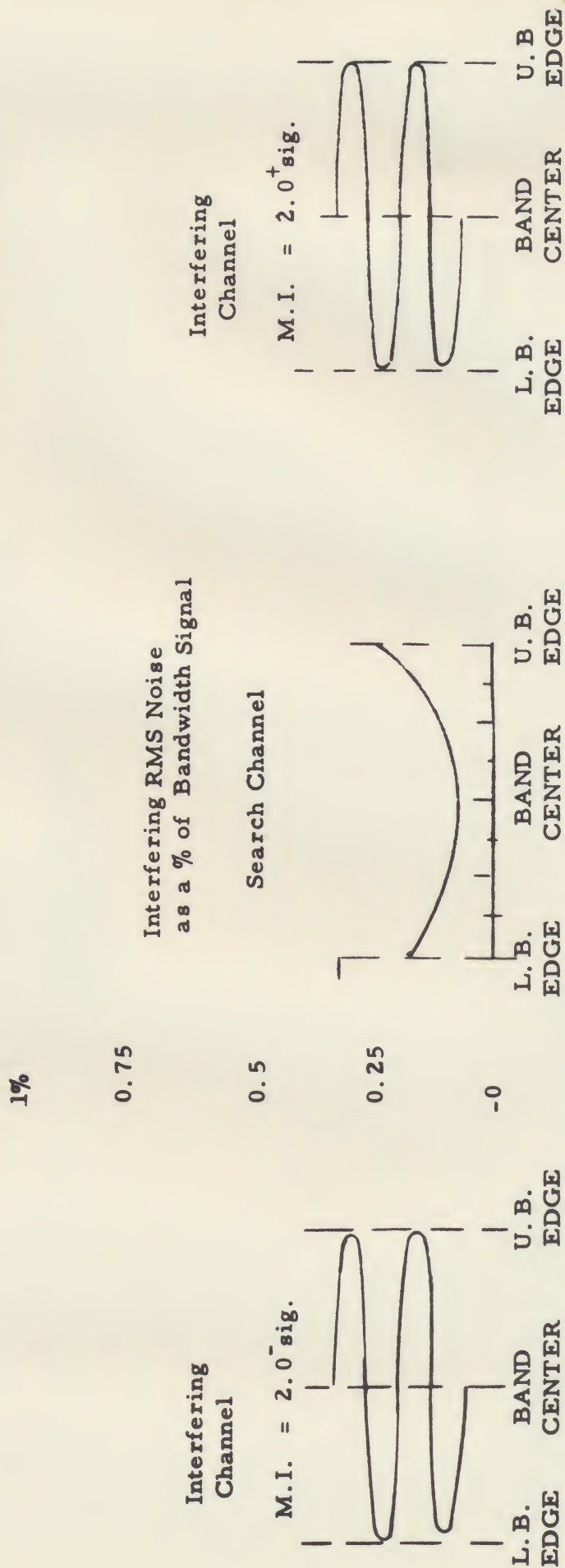
LBE

BC

UBE

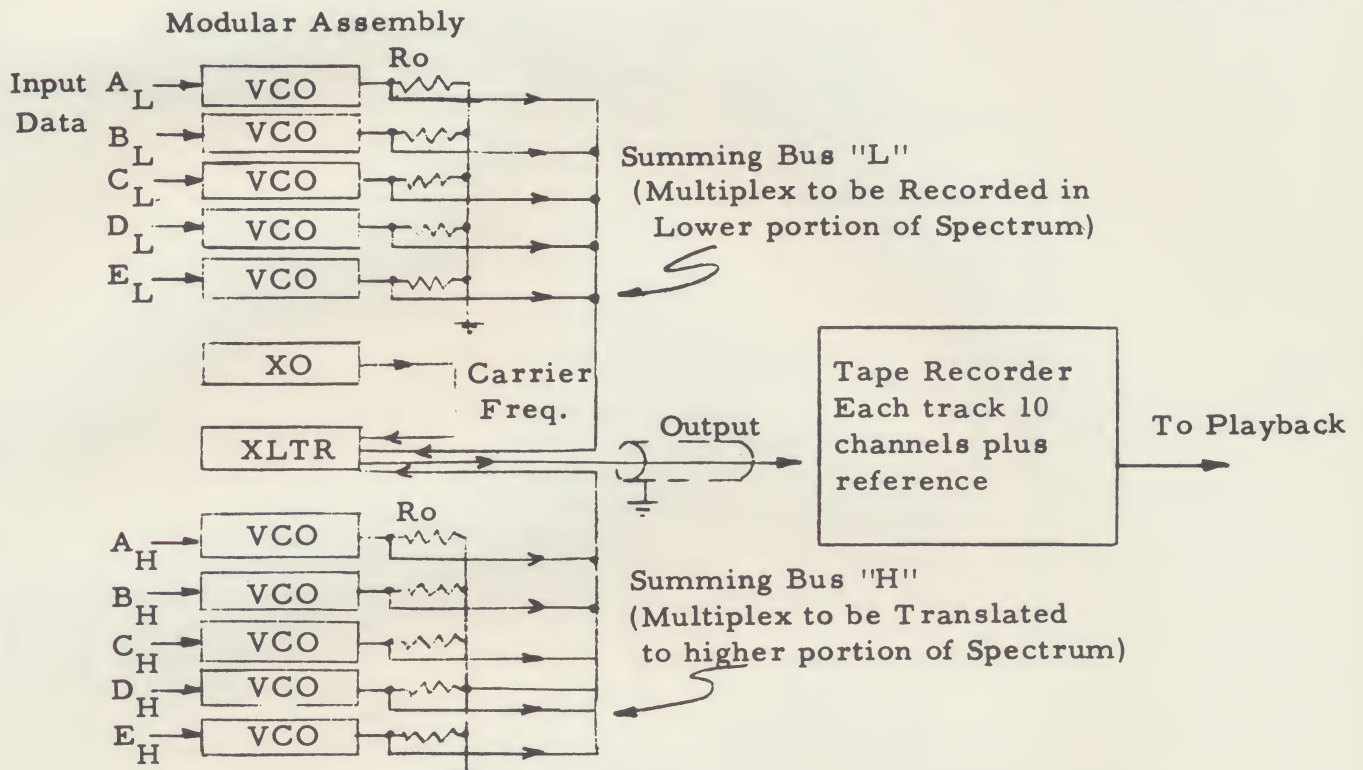
FIG. 4

MEASUREMENT OF ADJACENT CHANNEL
INTERFERENCE OF A CONSTANT BANDWIDTH
MOD. INDEX = 2.0 SYSTEM WITH MOD. I. = 2.0 SIGNALS ON ADJACENT CH.
OUTPUT LOW-PASS FILTER = 5 POLE LINEAR PHASE
GUARD BANDWIDTH = 7/8 CHANNEL BANDWIDTH

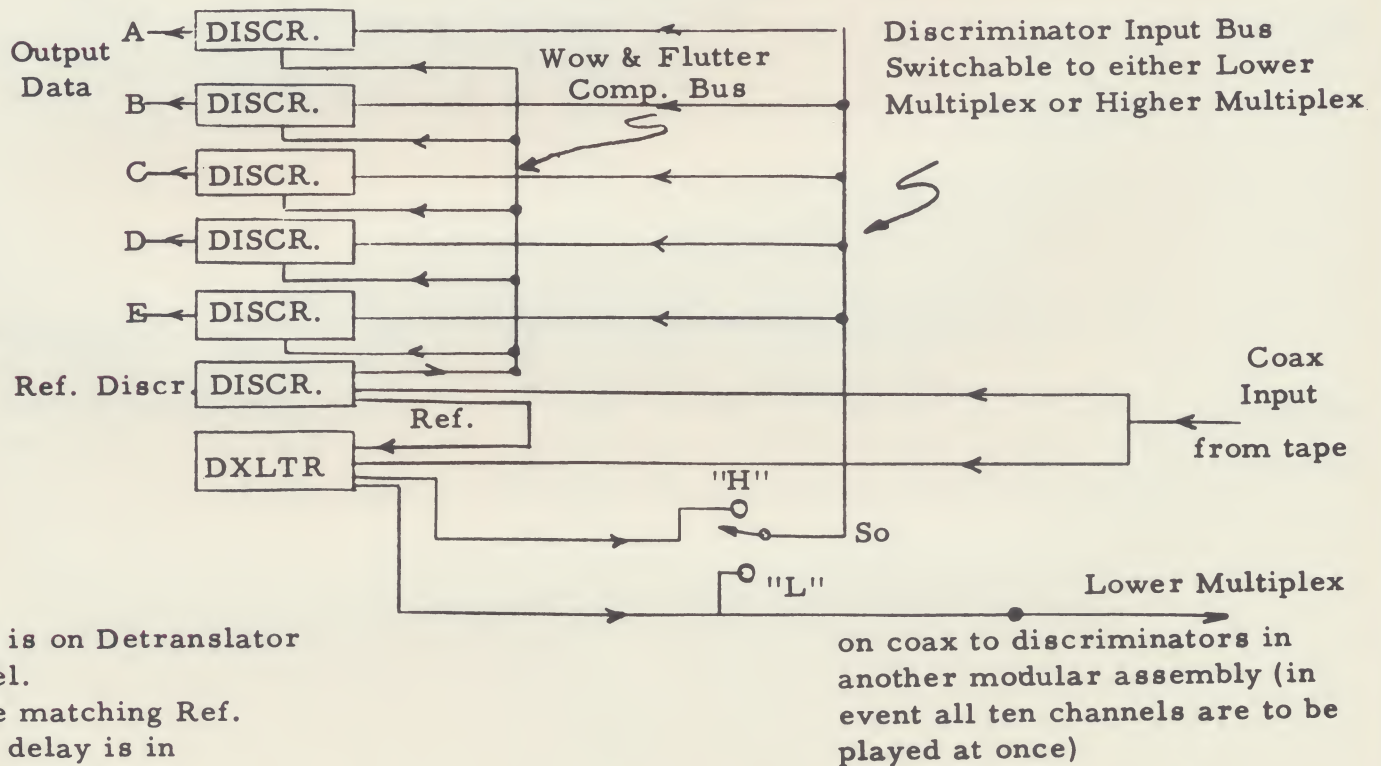


1. Record

VCO--Voltage Controlled Oscillator
 XLTR--Translator
 XO--Crystal Oscillator
 DISCR.--Subcarrier Discriminator
 DXLTR--Detranslator



2. Playback

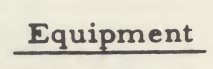
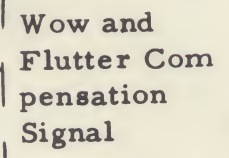


NOTE:

1. So switch is on Detranslator front panel.
2. Delay line matching Ref. Bandpass delay is in Detranslator.

FIGURE 5 - TYPICAL 10 CHANNEL RECORD-PLAYBACK CONFIGURATION

Outputs to Discriminators



10 V. C. O. 's
1 Xltr
1 Xtal Osc.

5 Data Discrim.
1 Ref. Discrim.
1 Detranslator
Plus Tuning Units

FIGURE 7

STUDY OF NOISE IN TEN FM CHANNELS
RECORDED ON A 100 KC TAPE RECORDER.
PLAYED BACK WITH TAPE SPEED COMPENSATION.

